OPTICAL PROPERTIES OF THE LOWER ATMOSPHERE OF VENUS (On the Interpretation of the Measurements for the "Venera-8" Automatic Interplanetary Station)

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OPTICAL PROPERTIES OF THE LOWER ATMOSPHERE OF VENUS
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ABSTRACT

The results are presented from the interpretation of the illumination measurements in the lower atmosphere of Venus in the wavelength λ region of 5,000-8,000 Å. These measurements were obtained with the equipment installed on board the "Venera-8" space probe. In order to construct an optical model of the lower Venusian atmosphere, the asymptotic theory of transfer of monochromatic radiation in a multilayer atmosphere was applied. The optical characteristics were determined from the relative variations in the measurements of: /3*

$$E_{\downarrow}(h) / E_{\downarrow}(h_o), \quad \frac{1}{E_{\downarrow}(h)} \cdot \frac{dE_{\downarrow}}{dh} .$$

The observational data agree well with the following optical model of the atmosphere. The atmosphere consists of two layers sharply differing from each other in their optical and physical characteristics. The lower, purely gaseous layer--extending from 0 to 28 km--scatters conservatively in accord with Rayleigh's Law. The upper, cloudy layer--extending from 28 to 65 km--absorbs and scatters visible light nearly conservatively and has an effective optical thickness of 29-95. The upper part of the cloud layer--that part above 44 km--is more transparent than the lower part. Furthermore, the whole cloudy area is significantly

*Numbers in the margin indicate pagination in the foreign text.

more transparent to the long-wavelength radiation in the 6,300-8,000 Å band (particle albedo of $0.256-1.15 \cdot 10^{-3}$) than to the short-wavelength radiation in the 5,000-6,300 Å band (particle albedo of $0.25-2.56 \cdot 10^{-2}$).

* * * * *

The illumination sensor set up on the "Venera-8" space probe /5
measured the radiation scattered by the atmosphere in the region from 5,000 to 8,000 Å [1]. The measurements were taken on July 23, 1972.

The sensor picked up radiation coming from the whole upper hemisphere at heights from 50 down to 0 km. The angle between the direction of the sun and the radius vector to the given point (the angle of the sun) at the time of descent amounted to $85.5 \pm 2^\circ$ [1]. The spectral characteristics $f(\lambda)$ of the receiver are given in [1]. Here λ is the wavelength. The downward light stream $E_\downarrow(h)$ was summed via the following integral [1]:

$$E_\downarrow[\mathrm{lx}] = 350\int_{5000\,Å}^{8000\,Å} f(\lambda)\,E_\downarrow(\lambda)\,[\mathrm{W}/m^2\,Å]\,d\lambda \qquad (1)$$

The unit of measurement for the radiation integrated in (1) was conventionally called a lux. The experimental data obtained on the dependence of the illumination $E_\downarrow(h)$ on the height above the surface is presented in the figure.

The curve, drawn through the experimental points by the method of least squares, has two characteristic points ($h = 28$ km, $h = 34$ km) in whose neighborhood a sharp change arises in the gradient of illumination with height. In the first portions $0 \le h \le 28$ km, it would be natural to assume a model of a purely /6
gaseous medium, consisting 100% of CO_2.

In these hypotheses, the illumination $E_{\downarrow}(h)$ within this region will change in accord with the following law [2]:

$$E_{\downarrow}(h) = \left[1 - \frac{\frac{3}{4}\tau_{r.0}\, P(h)/P_0}{1/1-A_s + \frac{3}{4}\tau_{og}}\right] E_{\downarrow}(h_1). \qquad (2)$$

Here τ_{og} is the optical thickness of the gaseous component from 0 to 28 km; P(h) is the CO_2 pressure at height h; A_s is the albedo of the surface of the planet; h_1 = 28 km; and P_0 = 93 atm.

To show the possible validity of such a model, it is sufficient just to deduce from the experimental data some average value for τ_{og} over the spectrum and over height--a value valid for all $0 \leq h \leq 28$ km and satisfying the interval requirement $4 \leq \tau_{og} \leq 27$. Such a τ_{og} will give information on the spectral composition of the light in this region. Using (2), we obtain the following expression for :

$$\tau_{og} = \frac{4}{3(1-A_s)} \; \frac{1 - E_{\downarrow}(h)/E_{\downarrow}(h_1)}{P(h)/P_1 + E_{\downarrow}(h)/E_{\downarrow}(h_1) - 1} . \qquad (3)$$

Having replaced in this formula the ratios $E_{\downarrow}(h)/E_{\downarrow}(h_1)$ with values taken from the experimental curve and using data on the pressure within the gaseous atmosphere of Venus presented in reference [3], we obtain the following tabulated dependence of τ_{og} on height:

TABLE 1

h [km]	0	4	6	8	11	13	18.5	Average
$\tau_{og}(1-A_s)$	3.67	4.9	7.3	6.8	6.3	4.85	13	7

The average value of $\tau_{og}(1 - A_{s_o})$ amounts to about 7, which /7
for $A_s = 0$ corresponds to $\lambda = 7{,}000$ Å. A certain decrease in $\tau_{og}(1 - A_n)$ at small heights can be a consequence of increasing apparatus error as the space probe enters the high-temperature layers. Not excluded, however, is the possibility that this decrease is brought about by the presence of a noticeable reflecting capability of the planet with $A_s \doteq 0.4$. The average value of $\tau_{og_o} \simeq 7$ shows that, lower than 28 km, only red light--in the 6,300 Å $\leq \lambda \leq$ 8,000 Å range--penetrates.

Since the gradient $dE_{\downarrow}/dh^o$ above 28 km sharply differs from that of the gaseous layer, it is possible to conclude that in this region the prime role in light scattering is played not by a gas but by an aerosol. Taking 28 km as the lower limit of the aerosol cloud and 65 km as the upper limit [3], we obtain a geometrical cloud thickness equal to 37 km. Using a priori estimates of the optical thickness of the clouds [3, 4] and also using an estimate for the transmission function $V(h, \xi)$ at the level of $h = 46$ km for $87.5° \geq \arccos \xi \geq 83.5°$ the value

$$V(h, \xi) \leq 0.343,$$

it is possible to conclude that at heights below 46 km an asymptotic regime is operative for the scattering of solar radiation [5, 6, 2].

To determine (a) the transmission function of the atmosphere, (b) the spectral composition of the transmitted light, (c) the absorption coefficient α, (d) the albedo a for single scattering, and (e) the root κ of the characteristic equation, let us consider the following relationships:

$$\varphi(h) = \frac{1}{E_\downarrow} \frac{dE_\downarrow}{dh} (65 - h).$$

Using the expression for $E_\downarrow(h)$ from reference [6] and neglecting the derivative with respect to height $A'(h)$ of the albedo of the underlying layer [2] and also neglecting the term $\sigma\delta\kappa$ in comparison with $(3 - x_1) \cdot (e^{2K\tau_0} - 1)$, we obtain for $\phi(h)$ the following expression: /8

$$\varphi(h) = \kappa\tau_0 \left\{ 1 + \frac{2}{e^{2\kappa\tau_0} - 1} \left[1 - \frac{8A\kappa e^{2\kappa\tau_0}}{(e^{2\kappa\tau_0} - 1)[(1-A)(3-x_1)+4\kappa] + 8\kappa} \right] \right\} \qquad (4)$$

Here x_1 is the first coefficient in the decomposition of the indicatrix $X(\gamma)$ into Legendre polynomials; τ_0 is the optical depth in the cloud at a height level h and is equal to $\alpha(65-h)$ with α = constant; $A(h)$ is determined from the appropriate system of equations [2]; $\delta = 1.42$ and the values for κ, τ_0, and A in (4) are functions of the height and averaged over the spectrum of the transmitted radiation. The parameter at a given height depends on the form of the indicatrix and the value of a, the albedo for single scattering. In the case of a small intrinsic absorption ($1 - a \ll 1$), the parameter κ is determined from: $\kappa^2 = (3 - x_1) \cdot (1 - a)$ [6]. From equation (4) it is evident that $\phi(h)$ essentially is determined by the product $\kappa\tau_0$ and weakly depends on A, κ, and x_1. Thus, the coefficient in the second term, included in the square brackets, for $A = 0.8$–0.9 and $x_1 \sim 2$ decreases monotonically from 1 when $\kappa = 0$ to 0.2 when $\kappa = 0.05$. In Table 2, the values for $\rho(h)$ are presented as taken from the curve in the figure and also presented are values of $\kappa\tau_0$ calculated from equation (4) with $x_1 = 2$, $A = 0.8$, and $\kappa = 0.05$. The coefficient x_1 is chosen by starting from estimates of the degree of extension of the indicatrix (see the review in [3] and [4]). The value for the parameter κ is obtained by an a priori estimate coupled with the use of a value for the spherical albedo A_{SPH} from Irvine [7]. $A \cong 0.8_0$ is the albedo of the lower reflecting layer at the level of 28 km.

The analysis of the data presented in Table 2 shows that from 28 to 34 km the spectral composition of the transmitted radiation changes sharply; that is, the contibution of the short-wavelength part of the spectral band in the transmitted light currents increases with height.

In actual fact, for a fixed wavelength λ, $\kappa\tau_0(h)$ is a monotonically decreasing function of height.

TABLE 2.

h [km]	$\varphi(h)$	$\kappa\tau_0$	$H_{\bullet S_A}=65-h$ [km]
28	1.55	1.54	37
30	1.55	1.54	35
32	1.95	1.95	33
34	2.66	2.66	31
36	2.12	2.12	29
38	1.73	1.73	27
40	1.41	1.39	25
42	1.17	1.17	23
44	0.97	0.91	21

In the case when the average value $\bar{\lambda}$ for $\kappa\tau_0$ depends weakly on the height h, this monotonicity is preserved (34 km $\leq$ h $\leq$ 44 km), and, contrariwise, is disturbed for a strong dependence of $\bar{\lambda}$ on the height (28 km $\leq$ h $\leq$ 34 km). From the values of $\kappa\tau_0$ at 28 and 34 km, it is possible to conclude that--assuming α = constant within a cloud--the parameter κ_2 averaged over the subregion /9

[6,300 Å, 8,000 Å] is three times less than the parameter κ_1 averaged over the subregion [5,000 Å, 6,300 Å], that is

$$\kappa(h=34\ \mathrm{km}) = \frac{\kappa_1+\kappa_2}{2} = \frac{\kappa\tau_0(h=34\ \mathrm{km})}{\kappa_2\tau_0(h=34\ \mathrm{km})}\kappa_2 \cong 2\kappa_2 \tag{5}$$

from which $\kappa_2 = \frac{1}{3}\kappa_1$.

In the 10-km-long region from 44 to 34 km, a natural attenuation of the light occurs as a result of scattering and of intrinsic absorption in the aerosol, evidently without substantial change in the spectral composition.

By using the dependence of $\kappa\tau_0$ on the height as given in Table 2, it is not hard to estimate that the parameter κ_0 averaged over the 10-km segment [34 km, 44 km] is four times larger than the parameter averaged over the interval [44 km, 65 km], that is, the upper layers of the cloud layer are much more transparent than the lower layers. /10

Besides the relative dependence of the parameter κ on the height h and wavelength λ, it would also be possible from these measurements, in principle, to also determine the absolute value of the parameter κ; however, a significant indeterminacy in the angle of the sun and a relatively small height range in the cloud cover combine to make it possible to determine only the limits of the change of this parameter. Above all, the parameter κ can be found from the spherical libido, if it is assumed that the atmosphere is homogeneous and infinite in depth.

According to Sobolev [6],

$$A_{SPH} = 1 - \frac{4\kappa}{3 - x_1} \tag{6}$$

In Table 3 are presented the values of A_{SPH}, according to Irvine [7], and κ, calculated from (6) with $x_1 = 2$. In columns 4-6 are presented the parameters κ_0, κ^0, κ_1, κ_2, determined through the values of κ in the third column.

TABLE 3

λ [Å]	A_{SPH}	κ	κ^0	κ_0	κ_1	κ_2
5019	0.79	0.0525	0.0266	0.107		0.05
6264	0.94	0.015	0.0076	0.0307	0.0163	
7227	0.93	0.0175	0.00882	0.0357		

The corresponding values of the albedo for single scattering /11
are determined from the relationship: $1 - a = \kappa^2$. As follows from the sixth and seventh columns of this table, the ratio $\kappa_1/\kappa_2 = 3$ determined from the reflection by the cloud layer exactly coincides with the ratio determined from the transmission by the clouds (5). Knowing κ, it is not difficult to estimate the full optical thickness of the clouds and, consequently, the average volume coefficient of scattering. Thus, we have

$$\tau_0 \cong \frac{\kappa \tau_0 (h = 28 \text{ km})}{\kappa_2} \cong 95, \qquad (7)$$

$$\alpha = \frac{\tau_0}{H_{\text{cloud}}} = 2.57 \cdot 10^{-5} \text{ cm}^{-1}. \qquad (8)$$

Let us now show the uncertainty limits for parameter κ, brought about by the uncertainty in the angle of the sun [83.5°, 87.5°]. Using the expression for the transmission function $V(\tau_0, \xi)$ [6], let us derive equations for determining the parameter $\vec{\kappa}$. Since the equations are most easily of all written for the level h = 28 km, we shall first determine only the parameter κ_2 and then from relationships (5) we can also determine the full parameter κ. And so for κ_2 we have

$$0.0129 = \frac{\xi\, u_0(\xi)\, 8\kappa_2\, e^{-\kappa_2 \tau_0}(3-x_1)}{\left[(3-x_1)(1-A)+4A\kappa_2\right]\left[(3-x_1)(e^{2\kappa_2\tau_0}-1)+6\delta\kappa_2\right]} \qquad A = 1 - 1/1+\tfrac{3}{4}\tau_{og}, \quad \tau_{og} = 7 \tag{9}$$

Since the parameter $\kappa_2 \leq 1$, it follows from (9) that $\Psi \leq 86.5°$. Then in the range over which ψ may vary [83.5°, 86.5°], which /12 corresponds to a range for ξ of [0.061, 0.1132], the limits of uncertainty for κ_2 are [0.053, 1]. The uncertainty in κ_2 according to reflection data is [0.016, 0.034], brought about by the measurement errors of Irvine [7], which amount to ± 7%. Thus the most probable values for κ_2 are 0.016 – 0.053 and the value for $\psi \approx 83.5$.

In an analogous fashion, it is possible to obtain the corresponding intervals for κ_1 and τ_0--[0.05, 0.16] and [29, 95].

Thus, the atmosphere of Venus consists of two layers, strongly differing from each other in their optical and physical characteristics. The lower, purely gaseous layer, extending from 0 to 28 km, scatters conservatively in accord with Rayleigh's Law. On the other hand, the upper cloud layer, extending from 28 km to 65 km, absorbs and scatters visible light almost conservatively, i.e., $\kappa \ll 1$, and has a great optical thickness. The upper part of the cloud layer, situated above 44 km, is more transparent than the lower part. Moreover, the whole cloud layer is significantly more transparent to long-wavelength [6,300 Å, 8,000 Å] than to short-wavelength radiation [5,000 Å, 6,300 Å].

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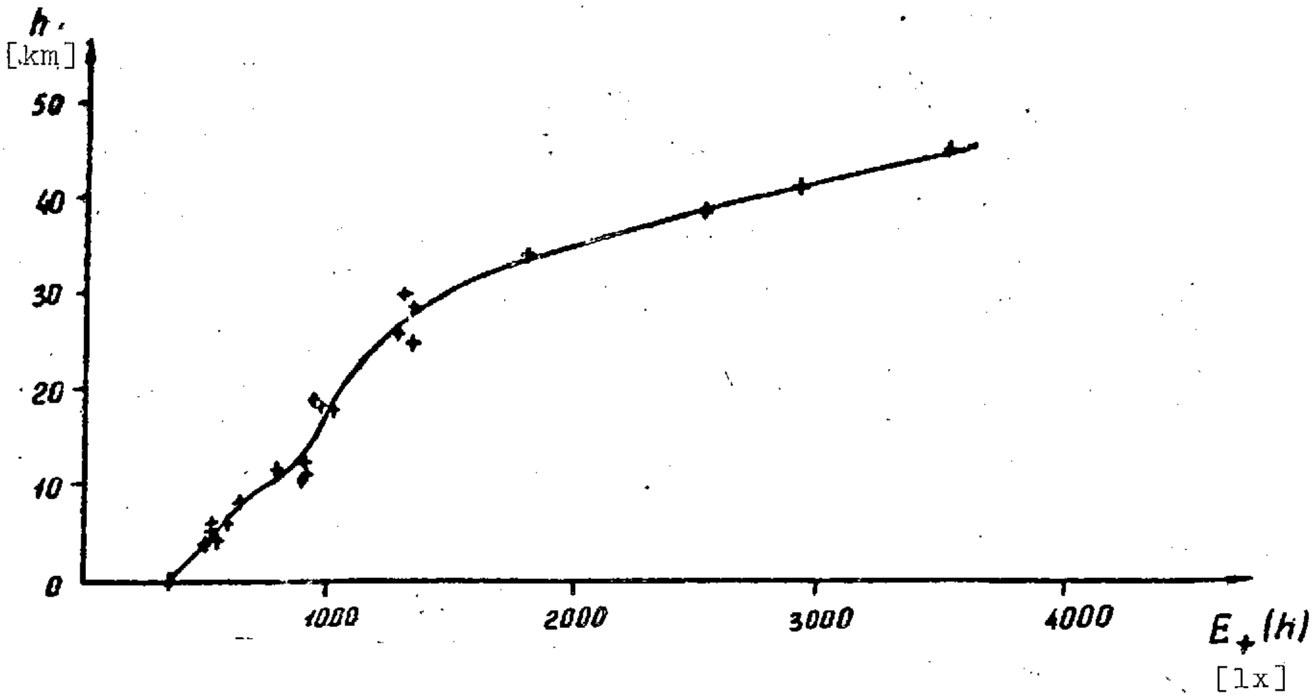

Dependence of the descending light stream $E_{\downarrow}(h)$ on the height. The crosses indicate experimental points.

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